Real World Experience with 6 GHz: Wi-Fi is the better option!

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Disclaimer: Opinions expressed are my own and are not necessarily supported by my affiliated institutions.

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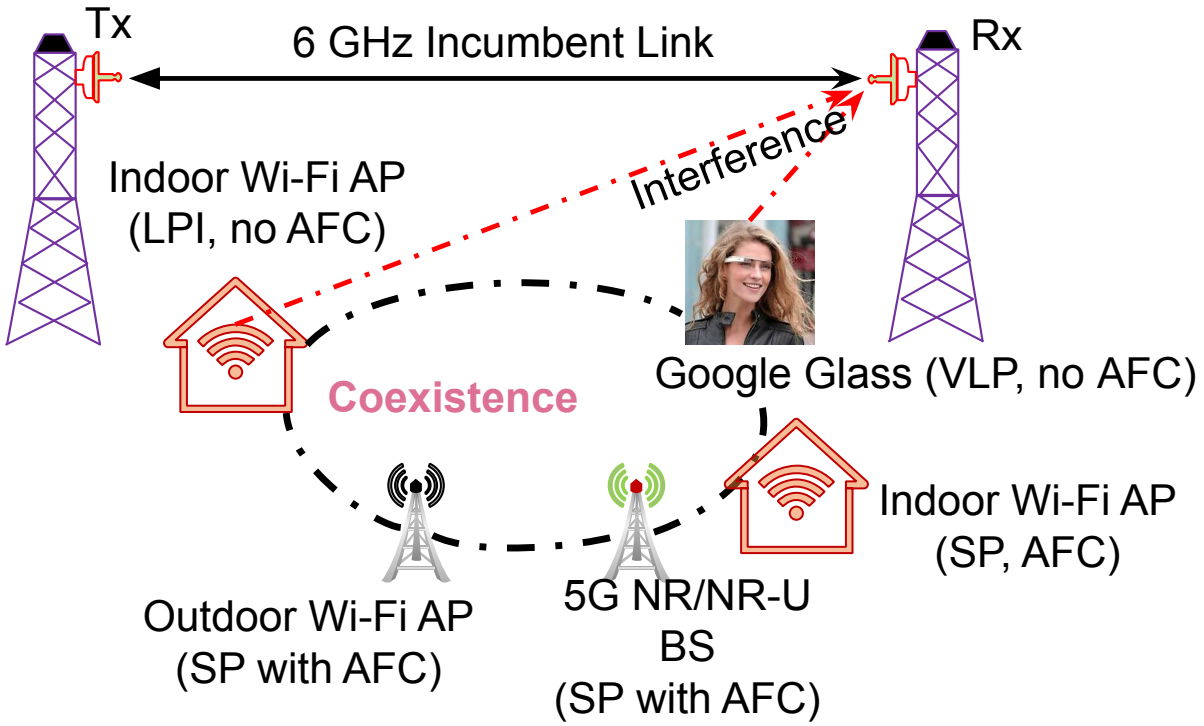
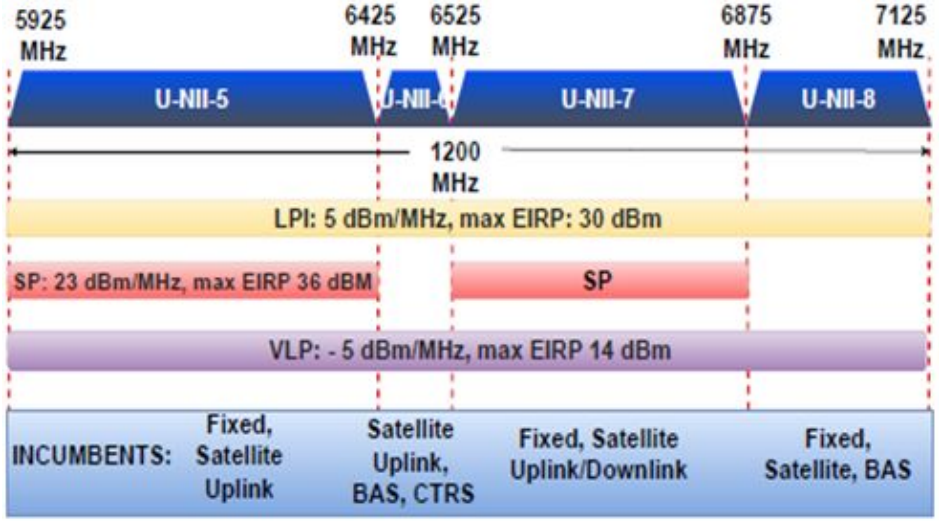
Spectrum and Connectivity Realities for 6 GHz and 6G

- **Mobile data demand growth is slowing, and > 80% originates or terminates indoors.**
  - Cellular networks are primarily deployed outdoors. Extremely power and spectrally inefficient to serve indoor use-cases from outdoor base-stations.
  - **20 to 30 dB building entry loss**, increasing with higher frequencies: energy inefficient.
- **Spectrum used by outdoor incumbents, e.g. government and scientific uses, can be reused with low-power indoors, without requiring complex sharing mechanisms.**
  - Access to higher bandwidths than exclusive high-power license, at mid-band frequencies. Can enable neutral host, small-cells.
- **Does this mean no high-power exclusively licensed spectrum for 6G?**
  - Exclusive spectrum is the tether ensuring ubiquitous coverage, especially outdoors. But how much is required, especially in 6 GHz and above? Are existing allocations enough for ubiquitous coverage? Supplementing with bands for indoor coverage, using neutral-host?
- **The 6 GHz Band**
  - Wide bandwidth, but many incumbents, poor propagation and high building loss.
  - Better suited for low-power unlicensed than high-power exclusively licensed.

6 GHz Developments in the U.S.

- Since 2020, the 6 GHz band (5.925 - 7.125 GHz) has been adopted fully in the U.S. for unlicensed but shared use and is being widely deployed in homes and enterprises.





Spectrum bands and U.S. Regulations in 6 GHz.

- SP deployments could only begin once the Automatic Frequency Control (AFC) systems were deployed and certified by the Federal Communications Commission (FCC) in February 2024.
- Most SP deployments today are enterprise deployments such as stadiums.

Our Contributions

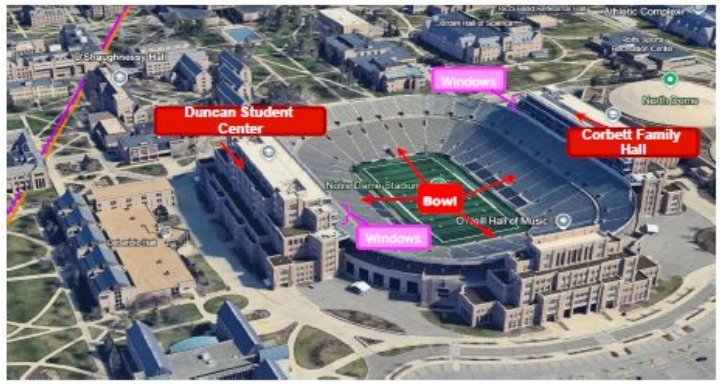
- Starting in 2023, my research group has been engaged in careful measurements of deployed Wi-Fi 6E in 6 GHz to understand coverage and potential for interference to fixed link incumbents and comparison with mid-band 5G.
  - University of Michigan, ~ 16,000 Wi-Fi 6E APs, all LPI
  - University of Notre Dame, ~ 900 SP Wi-Fi 6e APS in the stadium + hundreds of LPI APs in buildings
  - Measurements in many urban areas, including airports worldwide.
- Our main contributions are:
  - A first of its kind detailed data set of labeled indoor and outdoor measurements of SP and LPI APs.
    - https://sigcap.spectrumx.org/
  - Comparison of 6 GHz, 5 GHz and cellular performance when the Notre Dame stadium is at full capacity with 80,000 attendees.
  - Detailed analyses of coexistence of outdoor SP with indoor LPI under different conditions: fully occupied stadium and empty stadium.
  - Building Entry Loss measured with real APs.

Stadium Deployment

- The ND stadium consists of an open bowl area and three adjacent buildings anchored to the south, east, and west sides.
- There are three distinct environments: outdoors in the bowl area, indoors near windows in floors 7 - 9 of Corbett and Duncan, and indoor interior in floors 1 - 6 of the two building.
- About **900 SP Wi-Fi 6E APs** (Aruba AP-634) are installed outdoors in the stadium bowl: two SP APs are placed within a case and mounted on the handrail that splits the stadium section.

Measurement Environment.

Environment	Description
Out (Stadium Bowl)	The open area of the stadium bowl, with SP deployments
II (Indoor Interior)	Floors 1 - 2, Duncan Student Center, with concrete walls and no windows facing the stadium.
INW (Indoors near Windows)	Floors 7 - 9, Duncan Student Center and Corbett Family Hall, featuring long hallways with large double-pane low-E windows and glass doors to the stadium bowl.

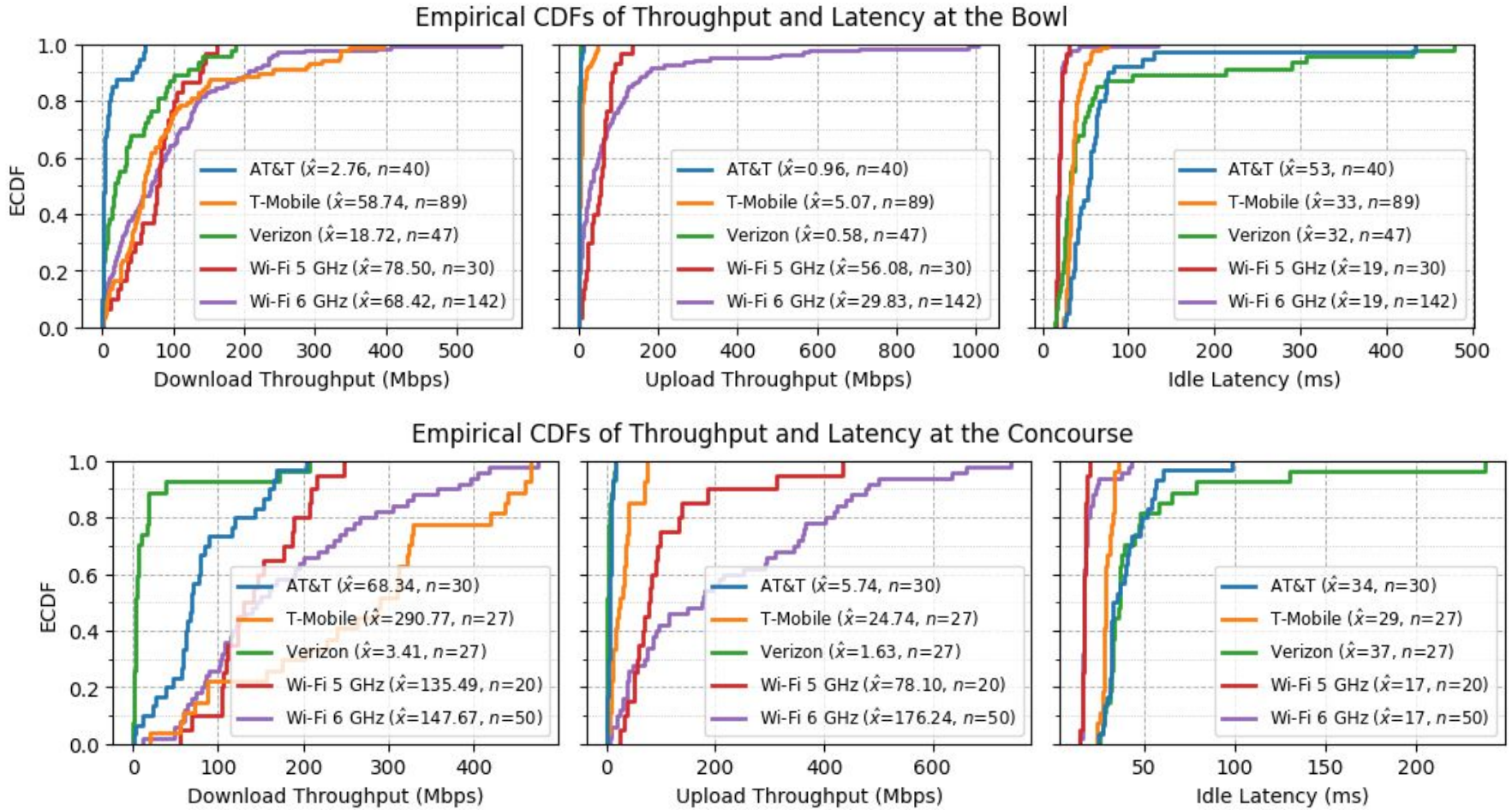


Measurement locations.

(a) Stadium bowl. (b) APs mounted on a handrail.

Wi-Fi 6E deployment at ND stadium.

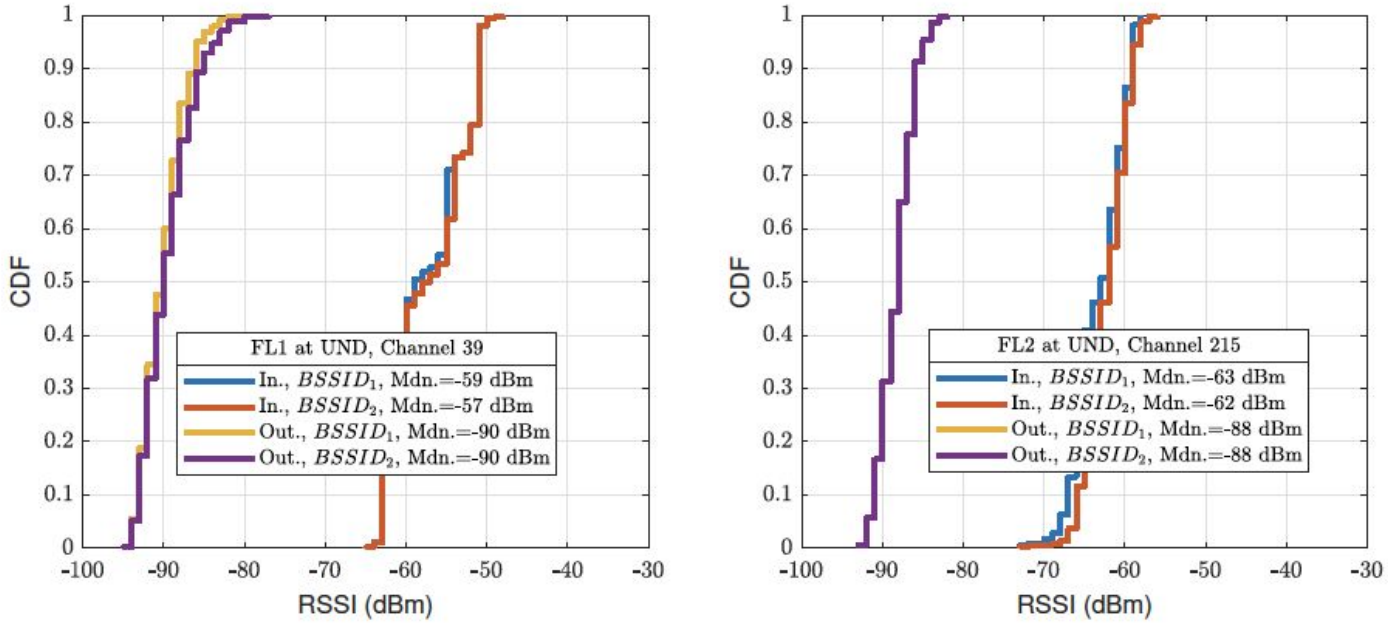
Comparison in the stadium between Wi-Fi and cellular



Measurement environment: Ookla speedtests, the stadium has a 5G DAS for T-Mobile

- **Key Takeaway:** Measurements with a full stadium (~80,000) indicate that Wi-Fi offers **improved downlink, uplink and latency over all cellular carriers.**

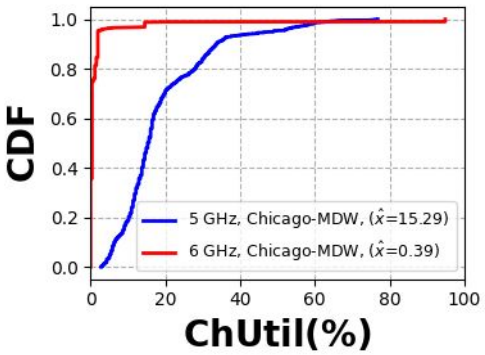
Measured Building Entry Loss (BEL) at 6 GHz at UND

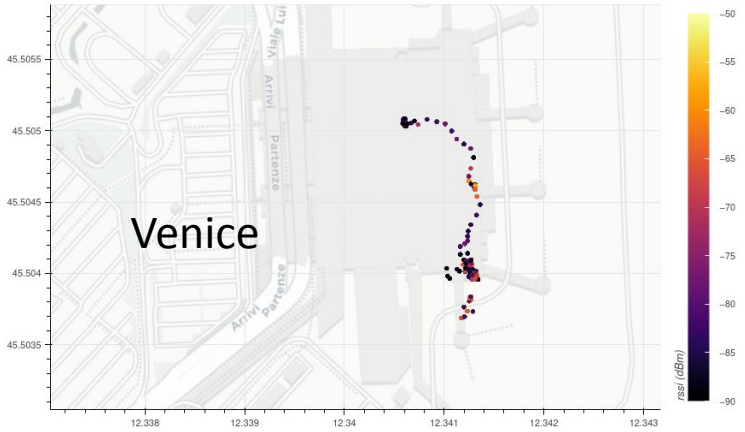


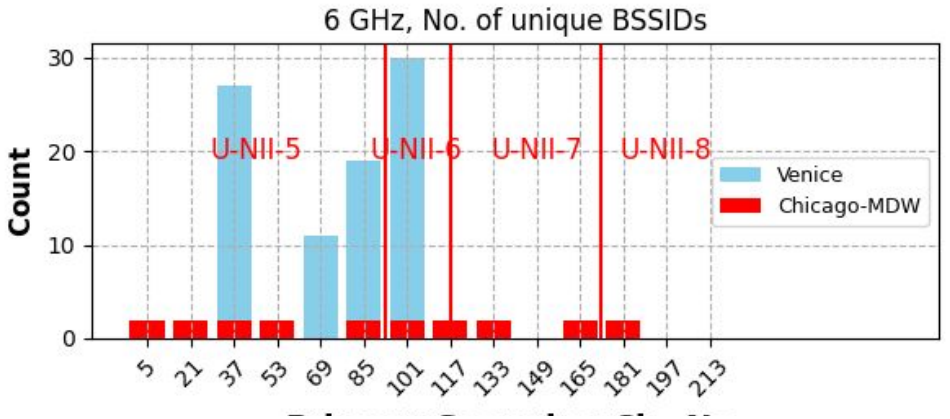
(a) For FL1. (b) For FL2.

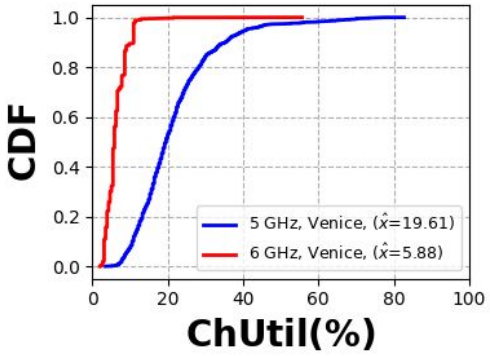
- Measured BEL through typical enterprise construction is 25 – 30 dB
  - This loss will also apply to cellular signals from outside.
  - The high BEL is good for Wi-Fi since it allows sharing between LPI devices and fixed link microwave incumbents. However, this will prevent indoor coverage from outdoor BSs if 6 GHz is used for cellular.

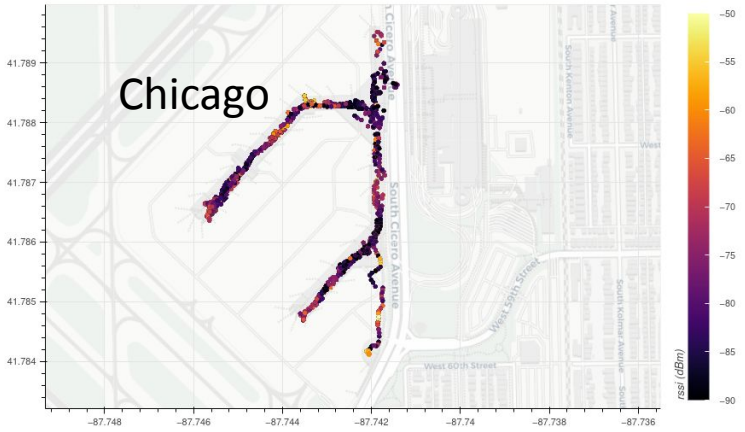
Wi-Fi Usage at Chicago Midway vs. Venice

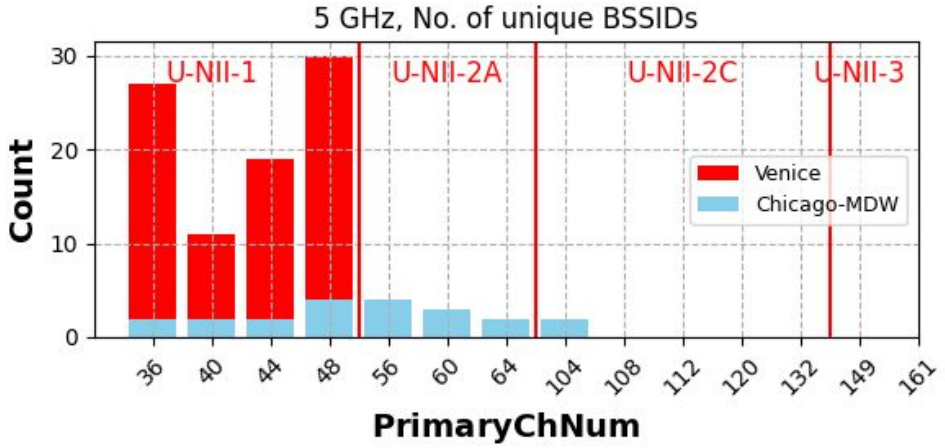






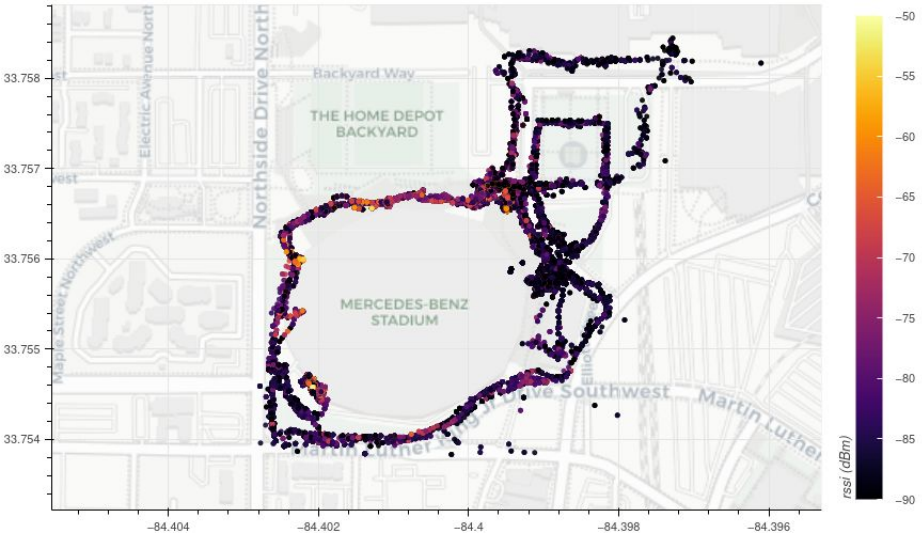






- Considering <u>only airport SSIDs</u>, the bandwidth is 20 MHz in Venice and 40 MHz in Chicago for both the 5 GHz and 6 GHz bands.
- In Venice, only the lower 6 GHz band is used, and with a smaller bandwidth, this results in higher channel utilization—**5.88% compared to 0.39% in Chicago.**
- Just adding the lower 6 GHz to Wi-Fi **will not make much of a difference to the Wi-Fi** experience due to continued use of 20 MHz channels.

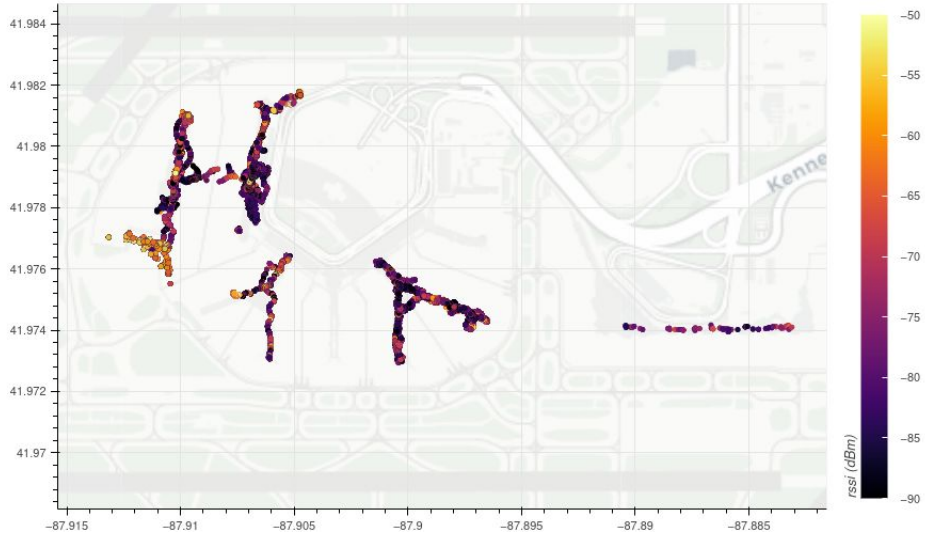
Wi-Fi 6E deployments in the U.S.: cities, stadiums, airports



SP Outdoors, Atlanta Stadium

LPI in NYC

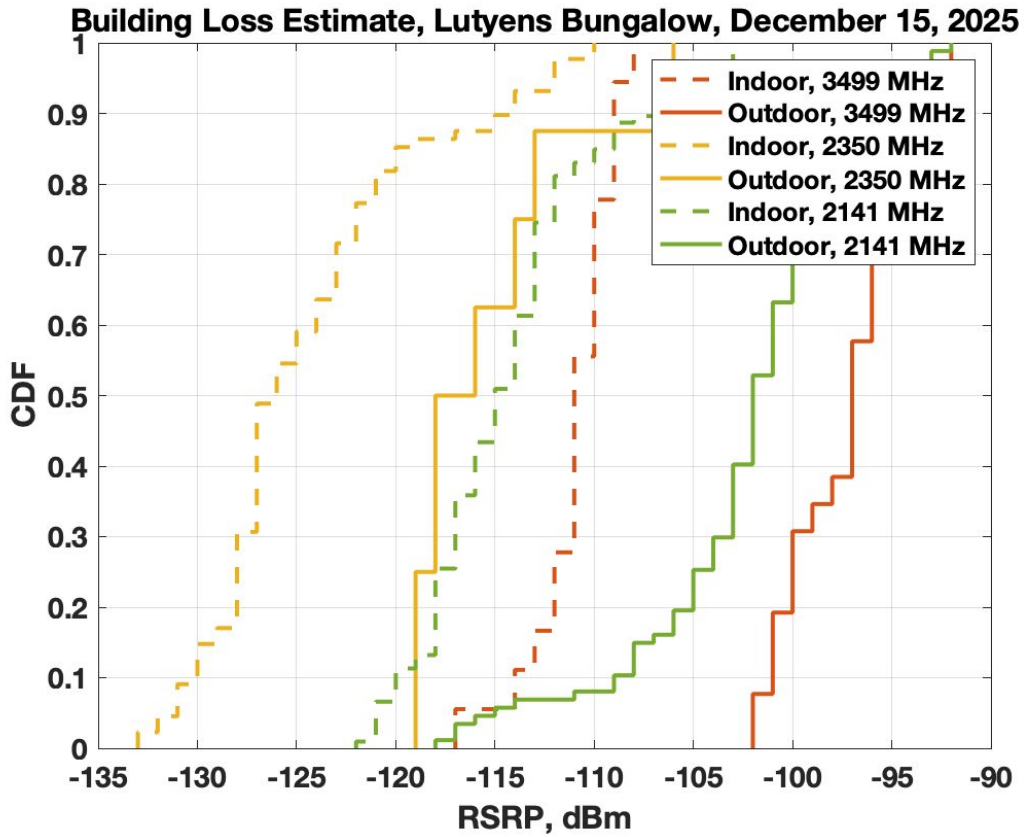
- As expected, the full bandwidth available for Wi-Fi 6E has resulted in many kinds of deployments, indoors and outdoors.
- By keeping the band unlicensed, many more applications can be supported.

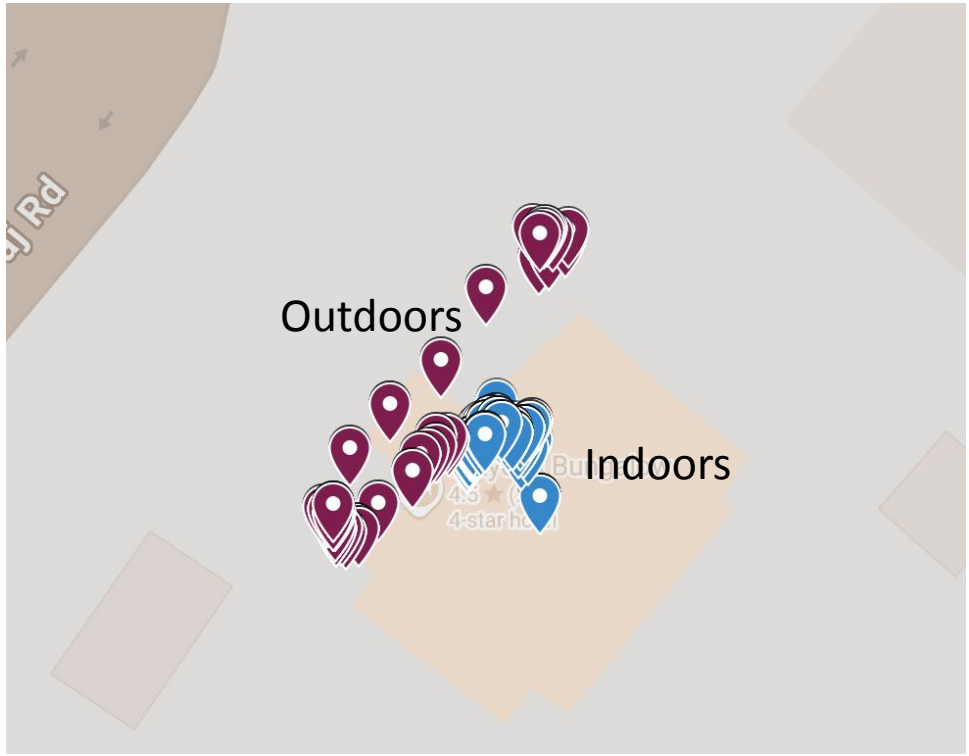


LPI Chicago O'Hare airport

LPI in San Francisco

Indoor/Outdoor RSRP in Delhi

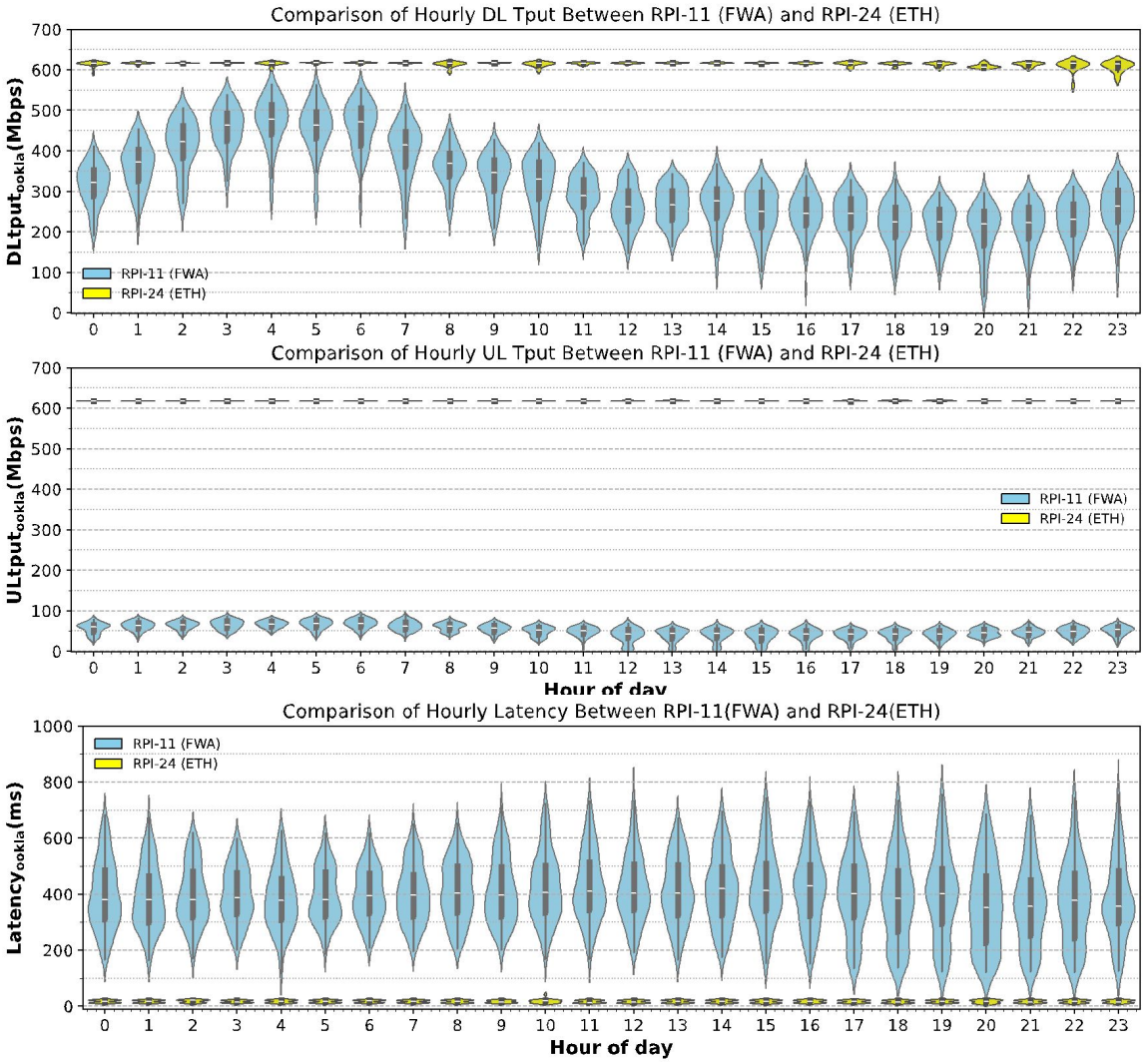




- Median BEL at least 15 dB at n77 (~3.5 GHz)

Is FWA a good application for 6 GHz?

- Real-world measurements with FWA in 2.5 GHz indicate that while peak DL throughput can match fiber in off-peak hours, the user experience at busy hours will not be very good.
  - This is unlikely to change with 6 GHz
  - May worsen if CPEs are installed indoors, like in 2.5 GHz
- The performance of uplink and latency are severely degraded compared to fiber.
- Key takeaways for FWA in 6 GHz:
  - Good user experience will require CPEs to be installed outdoors, raising costs.
  - Uplink performance will likely be degraded even more.



Conclusions and key takeaways for 6 GHz

- **Embrace propagation and building losses at 6 GHz instead of fighting it.**
  - Lower power, dense deployments indoors will serve connectivity needs better compared to high-power, outdoor cellular deployments.
  - Improved coexistence with incumbents.
  - Even 3.4 – 4 GHz cellular has poor indoor coverage, unless deployed indoors.
  - **DO NOT** repeat the mmWave mistake: 6 GHz is much lower in frequency but shares many characteristics of mmWave propagation.
  - Larger antenna arrays will be of limited use.

- **Explore hybrid sharing**
  - Cellular outdoors, Wi-Fi indoors in 6 GHz should be explored: again exploiting building loss instead of wasting energy trying to overcome it.

- **Learn from real-world experience in 6 GHz and 3 GHz**
  - Wi-Fi 6E/7 is very mature in the U.S. and is exceeding performance of cellular at 3 GHz in dense outdoor deployments like stadiums.
  - Indoor cellular performance even at 3 GHz is not meeting expectations, unless deployed indoors.

Papers on 6 GHz sharing

1) S. Dogan-Tusha, A. Tusha, M. I. Rochman, H. Nasiri, J. R. Palathinkal, M. Atkins and M. Ghosh, "Evaluation of Indoor/Outdoor Sharing in the Unlicensed 6 GHz Band," *2025 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, London, United Kingdom, 2025, pp. 1-9, doi: 10.1109/DySPAN64764.2025.11115954. https://arxiv.org/abs/2505.18359
2) S. Doğan-Tusha, A. Tusha, M. I. Rochman, H. Nasiri and M. Ghosh, "Spectrum Sharing Characterization Using Smartphones: Exploring 6 GHz Sharing Through Large-Scale Wi-Fi 6E Measurements," in *IEEE Communications Magazine*, vol. 63, no. 2, pp. 70-76, February 2025, doi: 10.1109/MCOM.001.2400325.
3) S. Dogan-Tusha, A. Tusha, H. Nasiri, M. I. Rochman and M. Ghosh, "Spectrum Sharing in 6 GHz: How is it working out?," *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Lucca, Italy, September 2024, pp. 791-795, doi: 10.1109/SPAWC60668.2024.10694058.
4) M. Ghosh, "Evolution of Sharing in 6 GHz," in *IEEE Wireless Communications*, vol. 30, no. 5, pp. 4-5, October 2023, doi: 10.1109/MWC.2023.10325444
5) S. Dogan-Tusha, A. Tusha, H. Nasiri, M. I. Rochman and M. Ghosh, "Indoor and Outdoor Measurement Campaign for Unlicensed 6 GHz Operation with Wi-Fi 6E," *2023 26th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Tampa, FL, USA, 2023, pp. 1-6, http://dx.doi.org/10.1109/WPMC59531.2023.10338962
6) S. Dogan-Tusha, M. I. Rochman, A. Tusha, H. Nasiri, J. Helzerman and M. Ghosh, “Evaluating the interference potential in 6 GHz: an extensive measurement campaign of a dense indoor Wi-Fi 6E network,” WiNTECH ‘23, Proceedings of the 17th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & Characterization, October 6, 2023, https://dl.acm.org/doi/abs/10.1145/3615453.3616518

Papers on mmWave and mid-band measurements

1. M. I. Rochman, W. Ye, Z. -L. Zhang and M. Ghosh, "A Comprehensive Real-World Evaluation of 5G Improvements over 4G in Low- and Mid-Bands," *2024 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Washington, DC, USA, 2024, pp. 257-266, doi: 10.1109/DySPAN60163.2024.10632844. https://arxiv.org/abs/2312.00957
2. M. I. Rochman, D. Fernandez, N. Nunez, V. Sathya, A. S. Ibrahim, M. Ghosh and W. Payne, "A comprehensive analysis of the coverage of 4G and 5G deployments," Computer Networks, Volume 237, 2023, https://doi.org/10.1016/j.comnet.2023.110060
3. A. Narayanan, M. I. Rochman, A. Hassan, B. S. Firmansyah, V. Sathya, M. Ghosh, F. Qian and Z.-L. Zhang, "A comparative measurement study of commercial 5G mmWave deployments," *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*, London, United Kingdom, 2022, pp. 800-809, doi: 10.1109/INFOCOM48880.2022.9796693.
4. M. I. Rochman, V. Sathya, N. Nunez, D. Fernandez, M. Ghosh, A. S. Ibrahim and W. Payne, "A comparison study of cellular deployments in Chicago and Miami using apps on smartphones," *Proceedings of the 15th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & Characterization*, pp. 61-68. 2022, https://dl.acm.org/doi/pdf/10.1145/3477086.3480843